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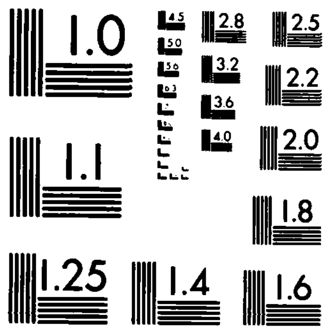

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REPORT SD-TR-85-01

The Role of Long Term Lamp Fluctuations in the Random Walk of Frequency Behavior of the Rubidium Frequency Standard: A Case Study

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A long term frequency stability test performed on an EG&G prototype Rb atomic frequency standard revealed excellent performance for an Rb atomic clock. Also, some classic Rb clock behaviors were observed, namely, long term frequency drift, spontaneous frequency jumps and random walk of frequency noise for long averaging times. A careful analysis of the complete test record disclosed that the spontaneous frequency jumps and the random walk of frequency noise can be attributed to the behavior of the clock's . . .

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discharge lamp. The long term frequency drift, however, was found not to be primarily lamp-related. Although results of only a single test on a single Rb clock are reported here, we believe that the results are applicable to Rb clock technology as a whole. cont. Key words include: see 1-7.

CONTENTS

FIGURES

PREFACE

We acknowledge the contributions of S. Goldberg, T. J. Lynch and W. J. Riley of EG&G, Electronic Components Division, for their careful reading of the manuscript and their helpful suggestions, M. Feldman of the National Bureau of Standards for supplying the data and R. A. Cook for help in the data reduction and analysis.

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I. INTRODUCTION

The long term performance of frequency standards has become increasingly of more concern as greater emphasis is placed on maintaining extended system synchronization and autonomy in modern communication and navigation systems. Where very long term (days to months) synchronization and high frequency stability have been major system concerns, atomic frequency standards have been relied upon to meet the stringent requirements. Presently the Rb gas cell and Cs beam tube frequency standards are used where extremely high performance over an extended period is mandated by system requirements; the use of the H-maser and the stored ion frequency standard are envisioned in the future to meet the anticipated increased demands of advanced communications and navigation systems.

Presently the Rb gas cell atomic clock is the most often used atomic frequency standard in high performance systems because of its small size, low weight, low power consumption and excellent short term performance. Some undesirable characteristics of the Rb clock include: frequency drift, spontaneous frequency jumps and random walk of frequency behavior. Spontaneous frequency jumps are generally unpredictable in magnitude and occurrence, but typically can be on the order of a few parts in 10^{12}, with periods of up to a few weeks between events. Modern Rb atomic clocks display frequency drifts ranging from a few parts in 10^{12}/d to as low as a few parts in 10^{13}/d; however, because there is no physical model describing this frequency drift, predictability of drift must be based on long term empirical observations. Random walk of frequency behavior is characteristic of Rb clock performance for averaging times greater than 10^4 s. Spontaneous frequency jumps, frequency drift, and random walk of frequency all affect the long term performance of the Rb clock and where extended system performance is required, system designers are sometimes forced to accept the larger, heavier, and more power consuming clocks, e.g., the Cs beam tube clock or H-maser to achieve better long term performance than that provided by the Rb clock.

Although it has been clear for some time that improvements in the long term characteristics of the Rb clock could be advantageously applied to both present and future systems, investigations of the physical phenomena causing these characteristics have been thwarted by the extensive time and concurrent costs associated with the necessary tests and measurements. We report here results of a recent long term frequency stability test of an Rb atomic clock. In addition to this test yielding a thorough measurement of the performance characteristics of one particular unit, and hopefully the general characteristics of similarly manufactured units, it also provided some insight into the possible physical phenomena responsible for different performance characteristics. Although no definitive conclusions can be reached based on a single test, albeit a very long test, the inferences drawn from this test are very strong and could serve as a guide to future clock design and testing.

II. DISCUSSION

To facilitate our discussion we have displayed a block diagram of an Rb atomic clock (Ref. 1) in Fig. 1. The essence of the Rb clock, in fact of any passive atomic clock, is that the output frequency of a quartz crystal oscillator is stabilized by referencing (locking) it to the frequency of an atomic transition. To accomplish this frequency locking, the atomic transition must be stimulated and detected in some manner. In the Rb clock, as shown in Fig. 1, the atomic transition is stimulated by a microwave field that is ultimately derived from the quartz oscillator's output and the Rb transition is detected by observing the transmission of light from the Rb discharge lamp through the cell containing Rb vapor. The sensed light is then used as the feedback signal to maintain the quartz oscillator's frequency. The stability that characterizes the atomic transition frequency is thus transferred to the quartz oscillator. The Rb transition frequency depends on various parameters such as temperature, magnetic field, power of the microwave field, intensity and wavelength of the light from the discharge lamp, etc. Thus, changes in these parameters can result in alterations in the quartz oscillator's output frequency unless through careful design the sensitivities of the Rb transition frequency to these particular parameters are brought essentially to zero.

A prototype Rb atomic clock (Refs. 2,3), designed and manufactured by EG&G, Electronic Components Division, for use onboard the NAVSTAR/Global Positioning System satellites, was subjected to a long term frequency stability test at the National Bureau of Standards (NBS) in Boulder, CO. (Ref. 4). The total test period was about 7 months and was conducted under thermovac conditions. The results indicated performance of this prototype Rb clock to be at the state-of-the-art level. The measured frequency stability of this unit was found to be among the best reported for any Rb clock, and thus we believe that careful analyses of the test data may lead to either the fundamental limitations or the means to advance the present Rb clock technology. In addition to monitoring the frequency of the Rb clock and comparing

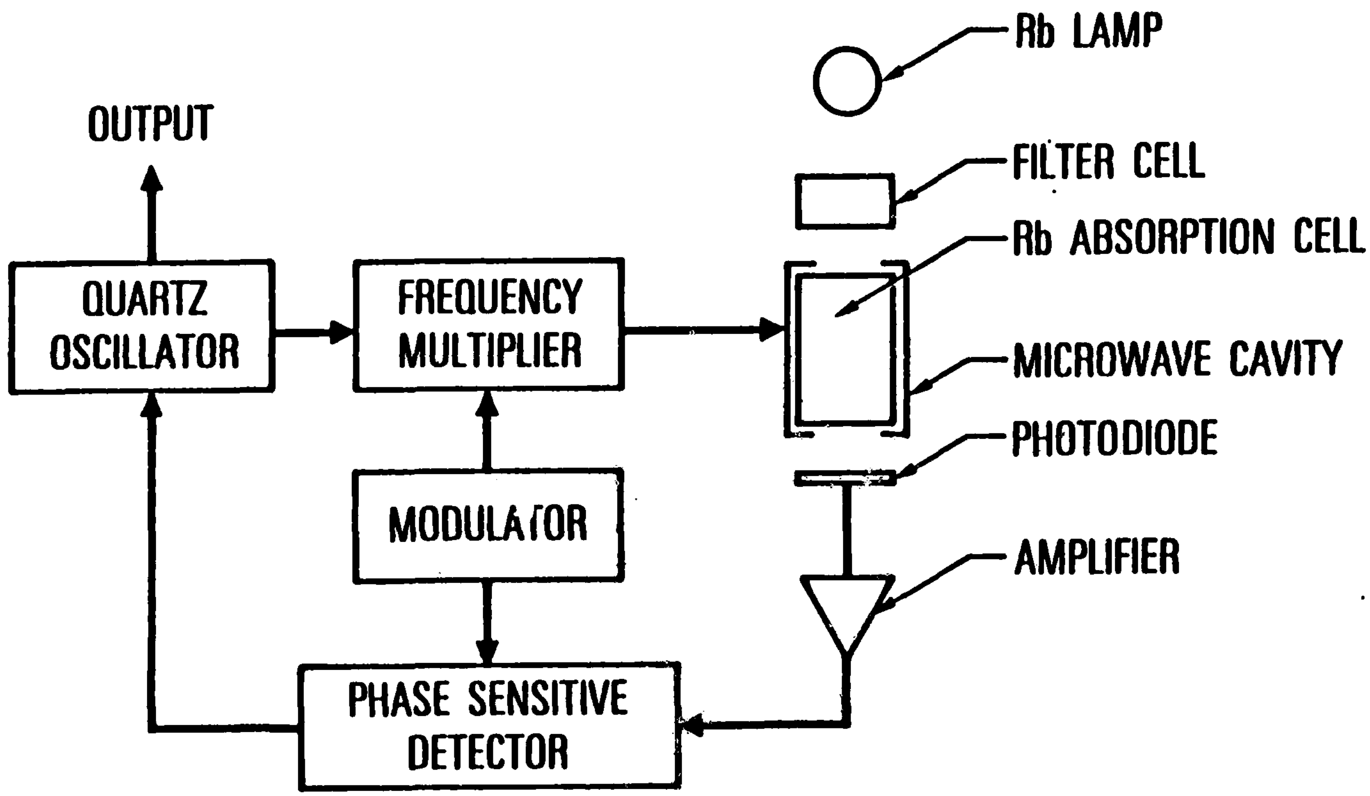

Figure 1. Block diagram of a Passive Rb Gas Cell frequency standard.

it to the frequency of the NBS clock ensemble, other clock parameters were recorded over the course of the test. In particular, a record was made of the dc current at the photodiode, which if all other parameters such as temperature, microwave power, etc., are constant, as was found to be the case in this test, is a direct measure of the clock's lamp output.

In Fig. 2 the clock frequency and light intensity recorded during the test are displayed. The two notable features are the jumps in the frequency, numbered in the figure from 1 to 8, and the continuous decline in both the frequency and light intensity. Very strong correlations have been found between the frequency jumps and the light intensity jumps for events numbered 2, 5, 6, 7 and 8. There are also correlations, although not as strong, between the frequency and light intensity for events 1, 2A, 3, and 4. The occurrence of the frequency jumps can be understood in terms of a physical model. In this model the Rb metallic reservoir, which is held in place in the lamp by thermal gradients, is broken apart, presumably under the influence of gravity, and the movement of small amounts of Rb metal in the lamp to areas of different temperatures causes a sudden change in the light output from the lamp which directly affects the frequency output of the clock (Ref. 3). The light and frequency jumps were not associated with the expected changes in the recovered signal. It seems likely, therefore, that the lamp intensity change is mostly in the lamp RF excitation power resulting from a change in the load presented to the lamp exciter due to Rb redistribution. From the frequency jumps it is evident that a decrease in light intensity results in an increase in the frequency of the clock. One would then expect that with the decreasing light intensity the clock should have exhibited a positive frequency drift. From the test record, it is clear that any contribution of the light intensity to the clock's frequency drift must be small compared to the primary and yet to be understood cause or causes of frequency drift in the Rb clock.

The effects of noise sources and random processes on the clock's frequency are measured in the time domain by the Allan variance (Ref. 5). To investigate the effects of statistical fluctuations of the light intensity on the frequency stability of the clock, we computed the Allan variance of the

light intensity. This result is displayed in Fig. 3. The plot exhibited in Fig. 3 can be thought of as the fractional intensity fluctuation from the lamp in the same way the "normal" Allan variance, $\sigma_y(\tau)$, that we associate with the clock represents fractional frequency fluctuations. The light intensity fluctuations result in clock frequency noise because of the light shift effect. This is the same reason that the spontaneous light intensity jumps result in frequency jumps. To convert the light fluctuation to frequency noise we derived a light shift coefficient by analyzing the frequency jumps, events 2, 5, 6, 7 and 8. From these jumps we derived the relation:

$$\frac{\Delta f}{f} \cong -(3 \pm 1) \times 10^{-10} \left(\frac{\Delta I}{I}\right) \tag{1}$$

where Δf is a change in clock frequency, f is the nominal clock frequency, and ΔI is a change in light intensity from the nominal intensity, I.

The EG&G Rb frequency standard design includes a discrete filter cell in a separate oven and the light shift parameters can be adjusted by varying the temperature of the filter cell. The filter cell temperature was chosen as a compromise between residual neutral density light intensity and lamp oven temperature coefficients of frequency. The measured neutral density light shift coefficient for this unit was -1.5×10^{-10} $(\Delta I/I)$, a value of the same sense and order-of-magnitude as observed for the jumps; but a neutral density light intensity change would normally result in a signal change in the same direction and of an equal or larger percentage magnitude than the light change. The actual signal change was small and generally in the opposite direction. Such an effect is often associated with a change in the RF excitation power applied to an Rb lamp operating in the "mixed" Rb-Kr mode.

The light shift coefficient of Eq. (1) is therefore empirically defined in terms of the observed behavior of this unit. Using the above relationship, we convert the Allan variance of light intensity as displayed in Fig. 3 to a predicted clock frequency Allan variance due to light fluctuations only. This result is displayed in Fig. 4 as the dotted line. For comparison we have also

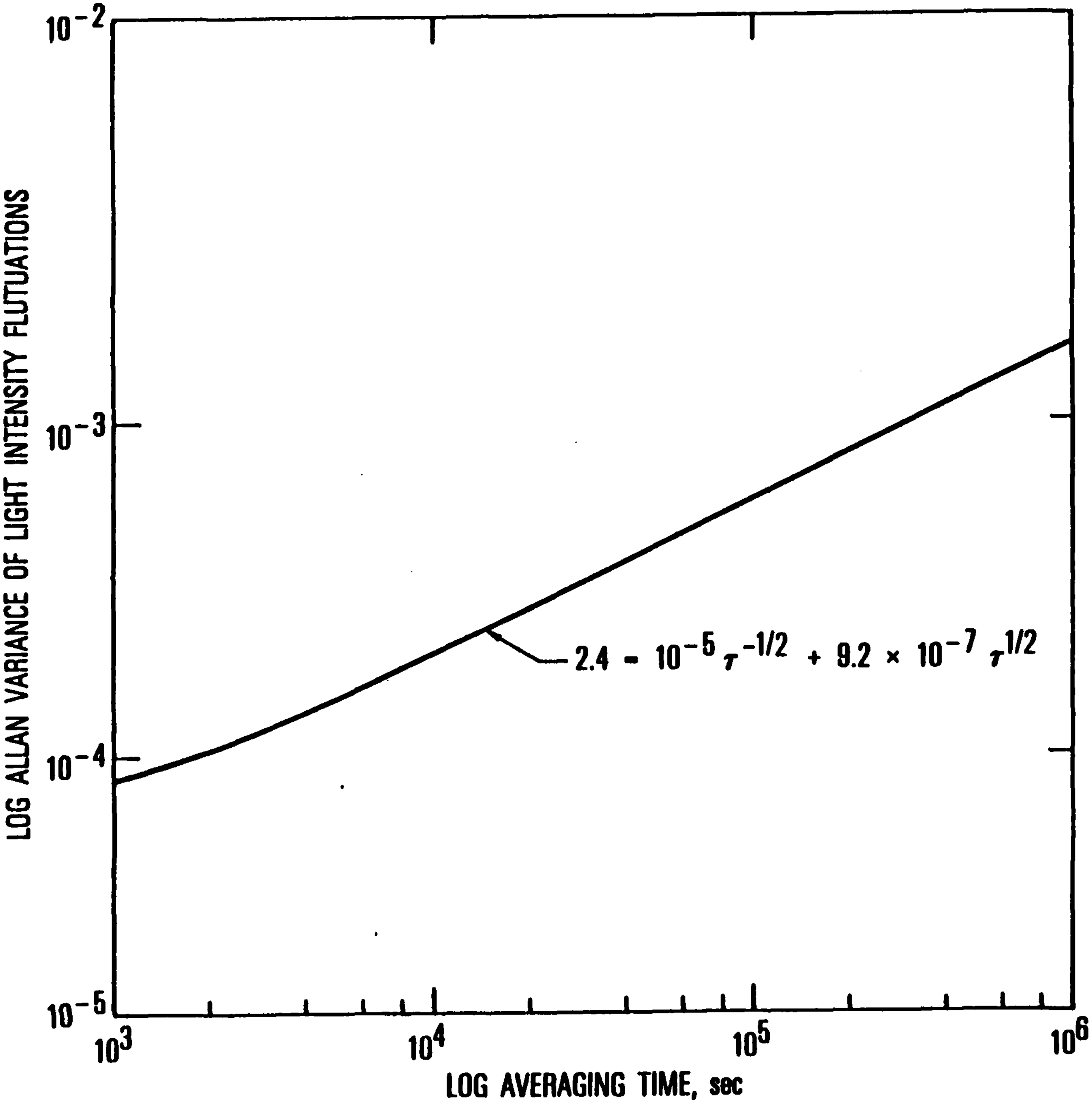

Figure 3. Allan variance of light intensity fluctuations.

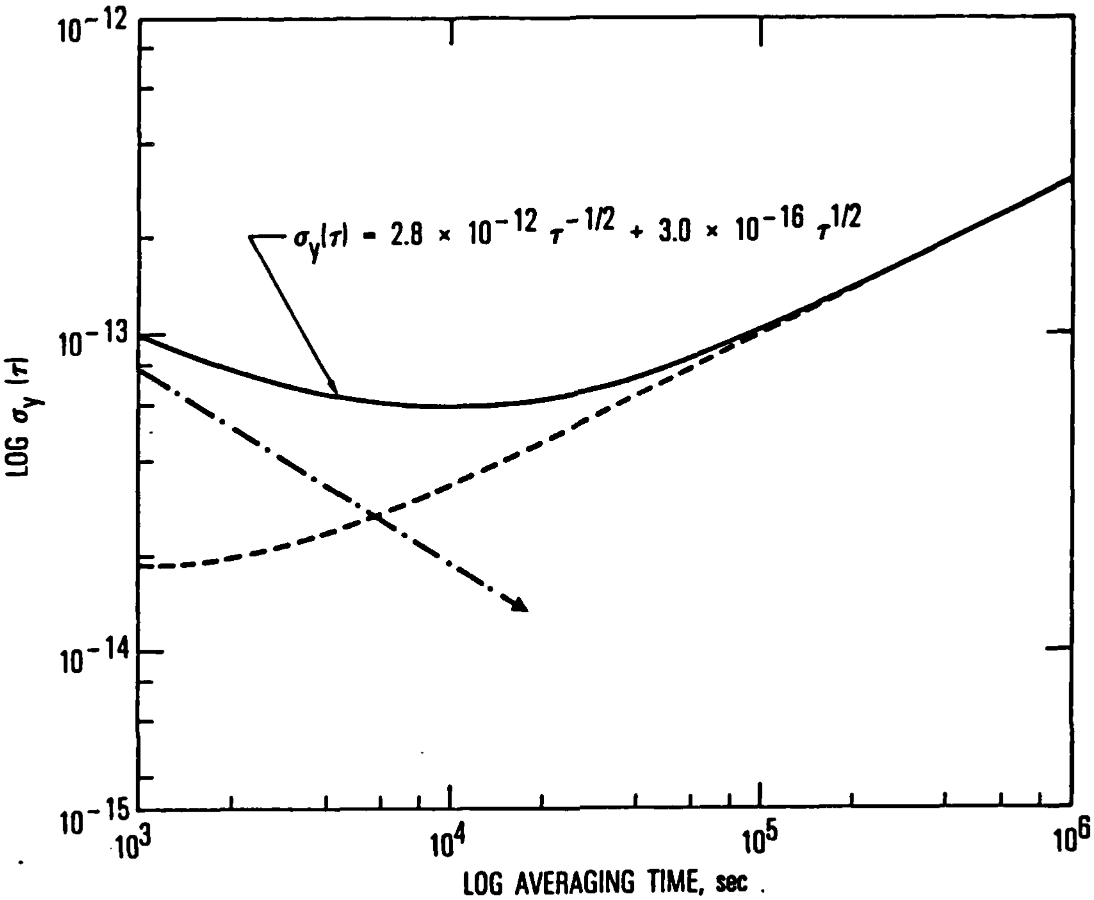

Figure 4. The solid line is the measured Allan variance, $\sigma_y(\tau)$, of the Rb clock's frequency fluctuations. The dashed line is the computed Allan variance of the clock's frequency fluctuations due to the light intensity fluctuations. The difference between these two curves is given by the dotted-dashed line and represents the clock stability in the limit of either a perfectly noise-free lamp or an Rb absorption cell with zero light shift coefficient.

plotted in Fig. 4 the measured clock frequency Allan variance.* It is interesting to note that the Allan variance over the entire data length can be completely described in terms of white frequency noise and random walk of frequency noise; i.e., this clock exhibited no flicker of frequency noise (Ref. 6). This may be due to either the fact that this Rb clock does indeed have state-of-the-art performance with no flicker of frequency noise, or that flicker of frequency noise postulated to exist in Rb clocks was simply an artifact because of insufficient test duration.

The Allan variance computed from the light intensity fluctuations converges to the measured clock Allan variance in the long term, i.e., for averaging times greater than 10^4 s. For shorter averaging times, especially less than 10^3 s, there seems to be only a negligible effect of excess light noise on the frequency fluctuations. This result seems entirely reasonable considering a previous analysis (Ref. 3) indicating that the short term performance of this clock is limited by shot noise. Our new result indicates then that the long term stability of this Rb clock is limited by the random walk of intensity of the Rb lamp. Because of the superb performance of this unit, we believe that this limitation is fundamental to all Rb clocks. The third line plotted in Fig. 4 is the difference between the measured Allan variance and that predicted by the fluctuations in the light intensity, which is then the Allan variance we would expect if the light noise were eliminated or drastically reduced.

*To compute these Allan variances, drift terms were removed from both the frequency and light intensity using a least squares method. Although it has been argued that this is not entirely proper in the presence of random walk noise, we believe that the discrepancy has little effect in terms of our comparison.

III. SUMMARY

We have considered the effects of light intensity changes on the performance of a prototype Rb atomic clock and have concluded that although frequency jumps could be attributed to light intensity jumps, light intensity changes were not the primary cause of frequency drift. This analysis has also investigated the relationship between clock frequency noise and light intensity noise. Our result shows that although light intensity noise has almost no effect on the short term performance of the clock, the long term performance appears to be significantly affected by the light intensity fluctuations. Although our finding rests heavily on our derived light shift coefficient, we argue that this coefficient is very good because it is derived in situ. Our results then indicate that an improved light source or a decreased light shift coefficient could dramatically improve long term Rb clock frequency stability. A second such prototype Rb atomic frequency standard did not exhibit such light and frequency jumps over a 7-month test interval. The only known difference was that that unit had a normal (60 μgram) rather than a high (474 μgram) lamp fill. Because the particular clock under test did display state-of-the-art performance, we believe that lamp noise is a fundamental issue which needs resolution to advance Rb clock technology as a whole.

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